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Tropical Cyclone Minimum Sea Level Pressure-Maximum Sustained Wind Relationship

by

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This paper investigates empirical relationships between maximum sustained surface winds and minimum sea-level pressure in western North Pacific tropical cyclones. The empirical equation developed by Atkinson and Holliday (1977) is reviewed and evaluated using 13 independent cases collected since the original study. New relationships were developed using the original dependent data set in Atkinson and Holliday and were tested also against the 13 independent cases. These new relationships were based on different assumptions for reducing observed peak wind gusts to one-minute sustained surface winds. (cont'd)

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CONTENTS

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TROPICAL CYCLONE
MINIMUM SEA LEVEL PRESSURE -
MAXIMUM SUSTAINED WIND RELATIONSHIP

I. INTRODUCTION

The U. S. Naval Oceanography Command Center/Joint Typhoon Warning Center (JTWC), Guam, has sought a reliable relationship between a tropical cyclone's minimum sea-level pressure and maximum sustained surface wind speeds since its formation in 1959. Many relationships have been developed over the years for the North Atlantic, western North Pacific and North Indian Ocean areas. JTWC personnel have also developed various relationships for the western North Pacific and these are discussed in the JTWC Annual Typhoon Reports (1961, 1964 and 1968). The most thorough study was produced by Atkinson and Holliday (1977). They derived the relationship

$$V = 6.7(1010-P_c)^{0.644}, \tag{1}$$

where V is the maximum one-minute sustained surface wind speed (knots), P_c is the minimum sea-level pressure (millibars) and a typical environmental pressure of 1010 mb is assumed. This equation is currently used operationally by JTWC.

This paper reviews the derivation of Equation (1) and tests it against a 4-year independent data set. The Atkinson and Holliday data and the independent data were also used to test other regression equations using latitudes and case-dependent environmental pressures (versus 1010 mb) as predictors.

II. REVIEW OF CURRENT JTWC RELATIONSHIP

The empirical relationship used at JTWC is based on an extensive data collection effort and the application of rigid screening criteria. The data set was comprised of 76 cases compiled from 28 years of tropical cyclone observations in the western North Pacific from 1947 to 1974. The data set consisted of minimum sea-level pressures (MSLP) obtained from aircraft penetrations or from station pressure observations and peak wind gusts obtained from recording anemometers. Peak wind gusts were then reduced to one-minute sustained winds using empirical gust factors derived by Sissenwine, et.al. (1973). These computed winds were then further adjusted from the anemometer elevation to a standard 10-meter elevation using the relationship

$$V/V_o = (H/H_o)^P, \tag{2}$$

where H_o is 10 meters, V_o is the wind at 10 meters, V and H are the wind and height of the anemometer and P is 1/16 as recommended by Sherlock (1953). A least squares regression was then used to fit the processed data to an equation of the form:

$$V = K(1010-P_c)^{\alpha} , \tag{3}$$

where K and α are the regression coefficients. The coefficients derived by Atkinson and Holliday were K=6.7 and α = .644.

In reviewing the original study, two possible improvements are suggested. The first involves the adjustments of the stations' peak gusts to arrive at 10-meter sustained winds. The Atkinson and Holliday study used expected gust factors from Table 13 of the Sissenwine, et al (1973). These gust factors were 50-percentile values. Applying these factors to a one-minute sustained wind would estimate a gust value which approximated the mean of the gust observations in the Sissenwine study. However, Atkinson and Holliday applied these gust factors to <u>peak</u> gusts. Applying mean gust factors to the peak gusts is questionable. It appears that the Atkinson and Holliday study should have used 90- or 98-percentile gust factors. These gust factors are 15-20% greater than the 50-percentile gust factors. Incorrect use of the 50-percentile would systematically overestimate computed sustained winds by 15-20%.

The second adjustment made to the raw data used by Atkinson and Holliday was a height adjustment for frictional effects using Equation (2). This height adjustment may have been unnecessary because peak surface wind gusts in tropical cyclones usually occur when momentum above the friction layer is transported downward to the surface in downrush winds associated with convective activity. The use of this relationship for tropical cyclone research is also questionable, because the majority of supporting studies were performed under three restricting conditions: (1) light to moderate winds, (2) flat, mid-western plains and (3) fair weather. This relationship is dependent on stability and surface roughness and always leads to a reduction in wind with decreasing height. The use of Equation (2) for adjusting the measured anemometer winds to a 10-meter height above sea-level is contingent upon anemometer location. For anemometers which are highly exposed and are able to measure non-frictionally reduced winds, Equation (2) may be applicable. However, a majority of operational anemometers are already recording frictionally reduced winds. For example, a recent study at the Royal Observatory, Hong Kong (ROHK) (Chin & Leong, 1978), concluded that Equation (2) was not valid for height reduction in tropical cyclone conditions at that station. Therefore, the authors did not use this height reduction in their data processing.

Besides the systematic biases discussed above, processing of the peak wind data as done by Atkinson and Holliday introduced a random error in the computed sustained winds. The error stems from the uncertainty inherent in the sustained wind versus gust relationship. Unquestionably, there is not a one-to-one relationship between sustained wind and gusts but rather a range of gusts corresponding to a particular sustained wind. Sissenwine, et.al.(1973) estimated the standard deviation of this range. Based on these standard deviations for the gust factors, it is estimated that an error of 20% is introduced in deriving the one-minute sustained winds. The reason for originally using peak gusts and then reducing them to sustained winds was to overcome the problem of estimating the one-minute averages directly from recording anemometers. The actual measurement of peak gusts is more reliable than measurement of sustained winds; but Atkinson and Holliday neglected the processing error in reducing peak gusts to sustained winds. In the final analysis, the authors believe that the one-minute winds could be directly measured within the 20% limit that the processing introduced. Additionally, other uncertainties which exist in the height adjustments and in the anemometers themselves indicate that the original screening criteria of the raw data could have been lessened in severity to increase the data base yet still remain within the error limits of the data processing.

III. INDEPENDENT DATA SET

An independent data set (Appendix A) was collected to test Equation (1). Criteria for the independent data set similar to the original Atkinson and Holliday study were established, but due to the discussion above some constraints were less restrictive as discussed below:

1. The original data were almost always selected in cases where the cyclone passed directly over or just to the left of the station. The new data were selected if the cyclone was within 30 nm of the station. The large majority of cases involved storms which passed directly over or to the left of the station. As in the original data set of Atkinson and Holliday, only wind observations from relatively small islands or coastal stations were used in the independent set.

2. Wind data were directly used from the station's hourly reports or from special wind reports at the time of

tropical cyclone passage. These observations are the sustained one-minute average wind speeds as defined in the Federal Meteorological Handbook-1 (1975). These independent wind data were not obtained from peak wind gusts nor reduced to a standard 10-meter elevation as were the dependent data.

Since the stations' strip charts were not available, the maximum one-minute sustained winds may have been missed. Therefore, results obtained from these data may be biased toward weaker sustained wind maxima.

3. Minimum sea-level pressures were obtained in a manner identical to the original study.

A total of 13 cases which fit the above criteria were selected from a 4-year period between 1975 and 1978.

IV. TESTS WITH INDEPENDENT DATA

Equation (1) was applied to the 13-case independent data set. The correlation coefficient was .86 and the standard error was 20 kt. (The correlation coefficient and standard error were .92 and 8.8 kt, respectively, for the dependent set in Atkinson and Holliday.) The standard error was larger by more than a factor of 2 for the independent data, and a bias toward stronger winds was evident in Equation (1), which overestimated 9 of the 13 cases. The average bias was +13 kt.

The large positive bias led the authors to recompute the one-minute sustained winds from the peak winds in the dependent set using the 90-percentile versus the 50-percentile gust factors (Table I) from Sissenwine, et al (1973). Following Chin and Leong (1978), no adjustments were made for anemometer heights above sea-level. This reprocessed dependent data were again fitted to Equation (3). The relationship derived in this manner is

$$V = 8.13(1010-P_C)^{0.572}, \qquad (4)$$

The correlation coefficient is .86. Figure 1 compares Equation (4) with Equation (1). Very little difference exists at low wind speeds, but large differences exist at the high wind speeds, particularly above 90 kt.

The independent data set was next applied to Equation (4) as it was to Equation (1). Correlation coefficients show little difference, but the average bias was reduced to +8 kt. The overall results of the two relationships are not significantly different as determined by a Student's t-test of correlation coefficients. Table II compares the two relationships on the independent data set.

TABLE I

1-MINUTE SPEED (KNOTS)	2-SECOND GUST FACTOR	
	PERCENTILE	
	50	90
20	1.30	1.58
30	1.28	1.50
40	1.26	1.44
50	1.24	1.41
60	1.22	1.40
80	1.18	1.38
100	1.15	1.36
125	1.12	1.33
150	1.09	1.29

Two-second gust factors with respect to the 1-minute steady wind speeds (Sissenwine, et. al., 1973).

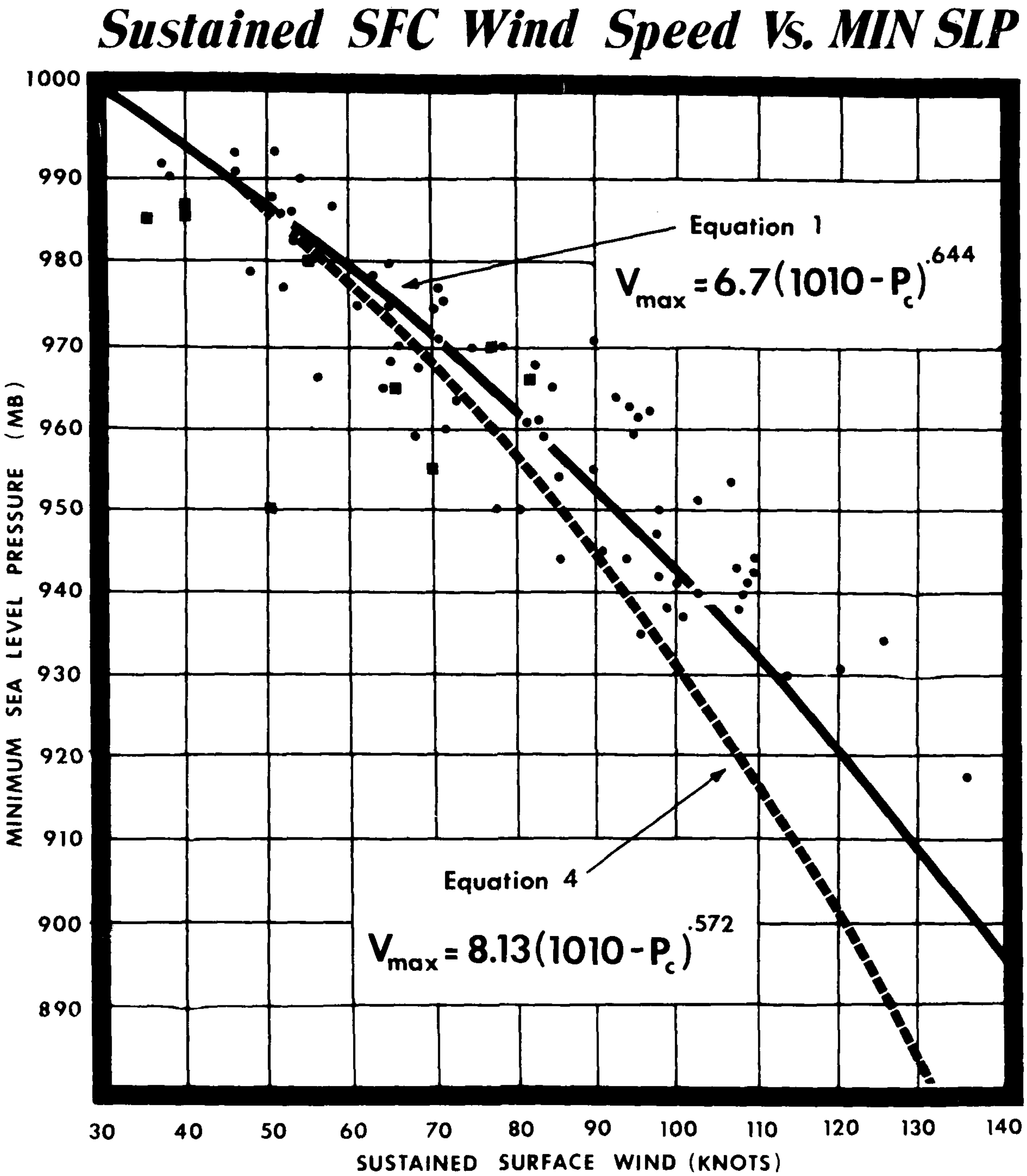

FIGURE 1. Results of the Atkinson and Holliday study (1977) are illustrated by Equation 1 (solid line) and respective, dependent data set (•). Equation 4 (dashed line) is a result of reprocessed dependent data (not depicted). The independent data set (■) is depicted for comparison.

TABLE II

RESULTS OF INDEPENDENT DATA APPLIED TO EQUATIONS DERIVED FROM DEPENDENT DATA

	Equation 1	Equation 4
Correlation Coefficient	.86	.86
Standard Error	20 kt	16 kt
Bias	+13 kt	+8 kt

V. TESTING OF ADDITIONAL PREDICTORS

Two additional predictors for relating MSLP to maximum sustained winds were evaluated. The form of the regression equation as specified in Equation (2) nonlinearly relates the pressure difference between storm center and surrounding environment ($1010-P_c$) to the maximum wind. This assumes that the environmental pressure is 1010 mb, a typical value in the western North Pacific. However, a further reduction in variance may be possible by estimating the environmental pressure for each case in the data set. Equation (2) would then take the form

$$V = K(P_e-P_c)^{\alpha}, \qquad (5)$$

where P_e is the estimated environmental pressure. P_e was derived using a 4-point average of the analyzed surface pressure at a 5-degree radius from cyclone center for all cases in the dependent and independent data sets.

In addition, although the maximum wind-MSLP relationship in a tropical cyclone approximates the cyclostrophic condition, it is possible that the Coriolis force plays a role, particularly in the larger tropical cyclones. Also, the typical environmental pressure of 1010 mb varies with latitude, and the inclusion of latitude as a predictor may explain some of the variance due to this effect. Consequently, Equation (2) was modified to include latitude as a predictor in the form

$$V = K(1010-P_c)^{\alpha}(\sin\theta)^{\beta}, \qquad (6)$$

where θ is the latitude.

Results using the estimated environmental pressure and latitude as additional predictors are summarized in Table III. The predictors explained less of the variance when applied to the independent data than Equation (4) without the predictors.

TABLE III

RESULTS OF ADDITIONAL PREDICTORS WHEN APPLIED TO INDEPENDENT DATA SET

RELATIONSHIP	REGRESSION COEFFICIENTS	CORRELATION COEFFICIENT	STANDARD ERROR
$V=K(1010-P_c)^{\alpha}$	K=8.13 α=.572	.86	16 kt
$V=K(P_e-P_c)^{\alpha}$	K=19.89 α=.348	.73	21 kt
$V=K(1010-P_c)^{\alpha}(\sin\theta)^{\beta}$	K=6.52 α=.605 β=-.137	.50	26 kt

VI. SUMMARY AND FURTHER RECOMMENDATIONS

This study shows that:

1. The form of the current JTWC pressure-wind relationship is superior to other relationships evaluated in this study.

(a) Equation (1) displayed a positive bias which increased with higher sustained wind speeds.

(b) The bias is primarily attributed to the calculation of maximum one-minute sustained winds by Atkinson and Holliday using 50-percentile rather than 90-percentile gust factors.

(c) Equation (4), which was computed using 90-percentile gust factors and no anemometer height adjustments, fits the independent data set better than Equation (1). However, the equations are not significantly different.

2. The use of variable environmental pressure (versus 1010 mb) and latitude in addition to MSLP did not improve the prediction of maximum winds.

3. The current JTWC pressure-wind relationship will continue to be used. The results of this study do not warrant any changes to this relationship.

Recommendations for further study include:

1. Increase the data base by including appropriate observations from unfortunate ships.

2. Include additional temperature gradient predictors from aircraft reconnaissance data.

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APPENDIX A

Independent data used to test minimum sea-level pressure--maximum sustained wind relationships.

Column 1: Name of cyclone

Column 2: Date (Zulu time)

Column 3: International (WMO) index number of station

Column 4: Maximum surface wind observed at station (knots)

Column 5: Cyclone's estimated minimum sea-level pressure at time of maximum wind

Column 6: Four point average of cyclone's environmental pressure (mb) at 5 degrees radius at time of maximum wind

Column 7: Latitude of station

1	2	3	4	5	6	7
CARMEN	15 AUG 78	47931	40	987	1007	27
IRMA	15 SEP 78	47805	40	986	1012	33
POLLY	17 JUN 78	47936	25	1001	1008	25
KIM	08 NOV 77	91218	55	980	1006	14
VERA	30 JUL 77	47918	103	926	1005	25
IVY	24 OCT 77	47991	70	955	1005	25
LUCY	01 DEC 77	91413	15	992	1010	10
THERESE	18 JUL 76	47842	65	965	1007	32
DOT	20 AUG 76	47929	22	991	1009	25
THERESE	16 JUL 76	47945	50	950	1006	25
RUBY	27 JUN 76	46810	35	985	1004	20
PHYLLIS	16 AUG 75	47898	77	970	1003	32
RITA	22 AUG 75	47899	82	966	1000	33

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